Appendix A

GTS Duratek Report

Geophysical Logging at Pit 9 Additional Probeholes, INEEL

Duratek Federal Services, Inc.
Northwest Operations
345 Hills Street
Richland, Washington 99352
(509) 376-7055 – Phone
(509) 372-1435 – Fax

GEOPHYSICAL LOGGING AT PIT 9 ADDITIONAL PROBEHOLES, INEEL

Prepared by:

Mr. James E. Meisner
Mr. Randall K. Price &
Dr. Russel R. Randall, Ph.D.

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1.0 INTRODUCTION

Remote sensing using borehole geophysics was successful in detecting the presence of Rocky Flats Plant (RFP) waste within the Radioactive Waste Management Complex (RWMC) study areas at Pit 9, Idaho National Engineering and Environmental Laboratory (INEEL). The target contaminants are ^{241}Am, ^{237}Np (daughter product ^{233}Pa), ^{239}Pu, uranium isotopes (^{238}U and ^{235}U), and chemical compounds containing chlorine. A secondary objective of geophysical logging was to determine if water saturation conditions awere present that could enhance contaminant release.

This report is organized to describe the borehole geophysical tools used in the investigation, including their principles of operation, calibration, field survey activities, and the results of the logging. The logging tools utilized to detect radioactive contaminants and chlorine are (1) a high resolution, high purity germanium (HPGe) spectral-gamma detector, and (2) a combination of a high-energy neutron source and HPGe detector (nGamma). Additionally, neutron-moisture and passive thermal neutron surveys were conducted to acquire measurements for the moisture profile and the fission rate of transuranic radionuclides. Optionally, azimuth HPGe log surveys for identifying the directional distribution of radionuclides will be used in subsequent investigation phases.

The borehole measurements were performed within steel cased probeholes (also referred to as boreholes in this report) that were placed in a geometric pattern in each study area.

The geophysical equipment used in the investigation is capable of measuring more parameters than the properties targeted in the investigation for Rocky Flats waste. This report includes a few examples of the additional parameters that can be retrieved from the these measurements along with possible analysis techniques by integrating multiple data sets, both from geophysical logging and from other available information. More information can be obtained from the geophysical logging data than is presented in this report.

The geophysical measurements unequivocally identified the target properties and estimated their concentrations. The accuracy of the computed concentrations of radionuclides are dependent on three general factors.

1. The accuracy of the concentrations assigned to the respective calibration models, which are traceable to National Institute of Standards and Testing (NIST) standards, for the radioactive materials.

2. The precision of the correction factors used to normalize the borehole measurements to the conditions of the calibration models. The target precision of the borehole measurements is to be equal to the precision of the calibration models. When available for confirmation purposes, independent verification measurements are reviewed.

3. The magnitude of unidentified environmental measurement perturbations that were not included in the algorithms to transform detector response values to concentration. There should be no major unidentified environmental measurement perturbations associated with the HPGe measurement of radionuclides. However, there may be some measurement perturbations, such as depressed neutron flux from high absorption of thermal neutrons, from measurements associated with the neutron-capture (nGamma) detector.

The algorithm for transforming log responses of chemical compounds containing chlorine to concentrations is still in development and therefore the associated log responses (chlorine) are reported as net count rates.

When the perturbing environmental parameters are identified and quantified, the raw data files acquired during this investigation can be reprocessed to incorporate the improvements.

2.0 BACKGROUND

Information presented in this section (2.0 - 2.2) was provided in *Operable Unit 7-13-14 Plan for the Installatin, Logging, and Monitoring of Probeholes in the Subsurface Disposal Area* (INEEL/EXT-98-00856, 2000).

Transuranic and low-level radioactive and non-radioactive hazardous waste at the Radioactive Waste Management Complex (RWMC) have been buried in Subsurface Disposal Area (SDA) pits, trenches, soil vaults, and on one aboveground pad since 1952. In 1970, the burial of transuranic (TRU) waste was discontinued, and in 1983 the burial of hazardous material was discontinued.

The Pits being investigated contain waste generated at the DOE Rocky Flats Plant (RFP), and from nuclear reactor testing activities at the INEEL. The RFP waste is the focus of a multi-stage waste remediation program aimed at mitigating potential environmental threats. Waste disposal records indicate that a variety of RFP waste materials (radionuclides and organic and inorganic compounds) were buried in the SDA.

Surface geophysical surveys were conducted to obtain a general understanding of the distribution of buried metallic debris and are correlated with disposal records to identify possible burial locations.

The data generated by the investigations (i.e. surface geophysical surveys, borehole installation and geophysical surveys, and soil vapor sampling) are to be used to refine parameters and reduce uncertainties in the risk assessment model, and support treatability studies.

Within this report, the term "waste seam" is used to describe the zone where waste was deposited and subsequently covered (or buried) by clean soil which is referred to as "overburden". The "underburden" is soil material below the waste.

2.1 Site Conditions

Soils at the RWMC Subsurface Disposal Area (SDA) are silt to sandy silt loess. The area of the pit was excavated to the uppermost surface of the basalt (approximately 15 ft below ground level in several pits) after which some local soil was laid back into the excavation to level the base of the excavation, (INEEL/EXT-98-00856, 2000).

During deposition of waste, drums and boxes were generally dumped in the pit by truck or bulldozer, while large items were placed in the pit by cranes. Soil cover was placed over the waste after daily or weekly operations, depending of the required procedures at the time of disposal.

Rocky Flats waste consisted of drummed sludge, assorted solid wastes, and cardboard boxes containing empty contaminated drums. Transuranic (TRU) radionuclides were contained primarily in the drummed sludge, with other waste products. Radioactive waste of fission and activation products contained in Rocky Flats waste include ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{234}U, ^{235}U, ^{238}U, ^{237}Np (daughter product ^{233}Pa), and ^{241}Am. The radioactive sludge, known as Series 74 sludge, is a target of planned remedial actions. The TRU radionuclides are contaminants of concern (COCs).

The organic compounds buried in the SDA that are the primary organic risk drivers include carbon tetrachloride, methylene chloride, and nitrobenzene. The waste also contains non-radioactive hazardous materials such as mercury, beryllium, asbestos, zirconium fines, solidified acids and bases, solvents and degreasing agents, and sodium and potassium salts.

2.2 Geophysical Logging Objectives

The objectives of the geophysical logging program are to identify and provide a relative quantification of the target contaminants, (i.e. carbon tetrachloride, ^{241}Am, ^{237}Np, plutonium isotopes, and depleted uranium) and determine if water saturation conditions may be present that could enhance contaminant release.

Four geophysical logging probes were deployed by Duratek Federal Services, Inc. (DFS), successor of Waste Management Technical Services, to satisfy the objectives of the logging program. A detailed description of the geophysical logging equipment is provided later. Briefly, the four logging probes used to achieve the logging program objectives are:

1. Neutron-Capture / Spectral-Gamma (n-Gamma) for identifying chemical compounds containing chlorine (eg. carbon tetrachloride is the primary chlorine compound expected to be present),

2. High Resolution passive Spectral Gamma for identifying the gamma-ray emitting radioactive contaminants (eg. ^{241}Am, ^{237}Np, plutonium, and uranium isotopes),

3. Passive Thermal Neutron for identifying radioactive fissionable materials (eg. ^{241}Am and plutonium isotopes) that may be beyond the detection range of the high resolution spectral gamma detector,

4. Neutron-Moisture for determining the relative water saturation conditions.

The borehole geophysical logging equipment operated by DFS is owned by United States Department of Energy (US-DOE) Hanford Operations. DFS modified the logging equipment, improved capabilities, and performed additional equipment characterization studies since the first deployment for Pit 9 to: (1) extend the dynamic range, (2) increase the maximum log depth for passive spectral gamma and passive thermal neutron, (3) increase logging efficiency, and (4) improve understanding of the nGamma system response characteristics.

1. The dynamic range of the passive spectral gamma detector was extended by improving the shape of the electronic signal transmitted from the detector to the logging truck (i.e. reducing the length of the logging cable from 600 ft to 100 ft) and increasing the signal processing speed of the electronics.
2. The maximum log depth was increased for the high resolution spectral gamma detector by separating it from the passive thermal neutron detector (which was in the same probe housing, below the gamma detector). The maximum log depth of the spectral gamma detector has been increased by 2.5 ft.

3. The logging efficiency was increased by configuring the INEEL borehole logging unit to be able to operate the DFS logging probes (i.e. reduced logging cable length, improved electronics, upgraded computer system, and upgraded the liquid nitrogen auto fill system).
4. The response characteristics of the neutron-capture / spectral-gamma detector (nGamma) was investigated in five ways by:
   (1) Constructing a borehole calibration model to analytically measure the change in chlorine, hydrogen, and iron gamma ray photo peak areas with changing chlorine concentration,
   (2) Extending the calibration accuracy to high concentrations of chlorine,
   (3) Bench marking (validating) a computer modeling code (MCNP) with the constructed borehole calibration model,
   (4) Replacing in the MCNP computer modeling code, the constituents of the borehole calibration model with the primary form of chemical compounds containing chlorine expected in the INEEL pits (i.e. 741 series organic sludge containing carbon tetrachloride), and
   (5) Comparing the calibration model response characteristics to that encountered while logging the SDA boreholes.

The boreholes in Pit 9 were installed adjacent to the initial 20 probeholes. A plan map of the relative borehole locations is shown in Figure 1.

A summary of the total casing depths, casing stickup, and dates of the main log survey is presented in Table 1. The casing stickup is the distance from the top of the casing (with the cap removed) to the ground surface. The total casing depth is the distance from the top of the casing (with the cap removed) to the bottom of the casing (including drilling tip), as reported by INEEL.

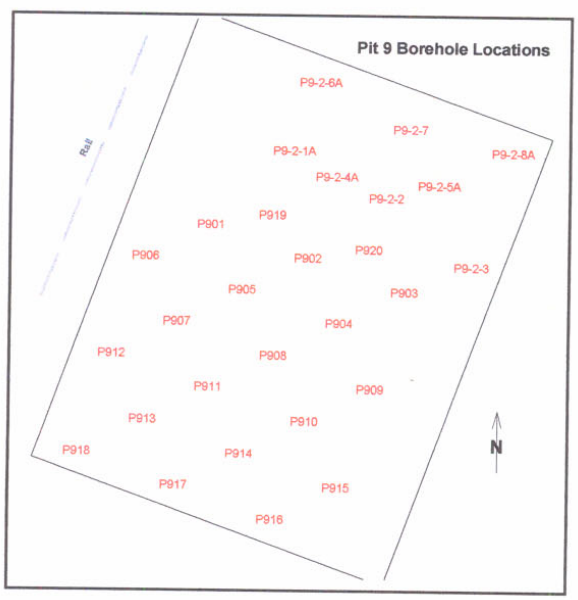

Figure 1 Borehole Locations Pit 9 (Initial 20 and 8 Additional)

Table 1 Summary of Logging Operations

Borehole ID	Casing Total Depth (ft)	Casing Stickup (ft)	Spectra Gamma Date	Moisture Survey Date	n-Gamma Survey Date	Passive Neutron Date
P9-2-1A	13.25	0.10	11/12/00	11/08/00	11/10/00	11/08/00
P9-2-2	12.70	0.11	11/10/00	11/08/00	11/10/00	11/08/00
P9-2-3	11.36	0.93	11/09/00	11/08/00	11/09/00	11/12/00
P9-2-4A	12.70	0.48	11/09/00	11/08/00	11/10/00	11/08/00
P9-2-5A	11.20	0.07	11/10/00	11/08/00	11/09/00	11/12/00
P9-2-6A	11.13	0.15	11/09/00	11/08/00	11/10/00	11/12/00
P9-2-7	11.17	0.10	11/10/00	11/08/00	11/11/00	11/12/00
P9-2-8A	9.77	0.20	11/10/00	11/08/00	11/09/00	11/12/00
P920	12.15	0.24	11/12/00	11/13/00	11/11/00	11/08/00

2.3 Project Quality Assurance/Quality Control

All logging operations and data analysis were performed in accordance with procedures outlined in the DFS Operational Environmental Monitoring (OEM) manual, which are referenced at the end of this report. The DFS procedures were evaluated prior to the initial logging project (Pit 9, February 1999) via an INEEL audit, and all concerns were satisfactorily addressed. In addition to the logging procedures, the DFS Quality Assurance Project Plan (QAPjP) identifies the implementing procedures to ensure compliance with governing regulations, standards, and codes associated with geophysical logging and analysis (ES-QAPjP-00-123). A review of operational readiness was conducted to the satisfaction of INEEL prior to commencement of logging activities.

3.0 DESCRIPTION OF THE LOGGING EQUIPMENT

The logging system, including the principles of the measurement, sensitivity, calibration parameters, and measurement specifications are discussed in Sections 3.1 through 3.5 for the logging equipment utilized in the RWMC subsurface disposal area investigations.

3.1 Logging System

Two logging vehicles were utilized. The Hanford logging truck selected for the previous RWMC borehole survey activities was utilized in this project. A second logging truck was assigned by INEEL to support the project. Both logging vehicles were manufactured by Greenspan, Inc. of Houston, Texas. The trucks were constructed to Hanford and INEEL specifications for use at the respective US-DOE nuclear waste sites. The vehicles are comprised of laboratory quality instrumentation adapted for borehole logging. The logging systems are self-contained for operating at remote sites. The systems are contained in a environmentally protected body mounted on a heavy-duty vehicle chassis and include the logging tools, surface instrumentation, and a winch system for positioning and maintaining communications with the logging probes. All of the logging probes deployed for RWMC logging were operated by the retrieval and data acquisition system on the truck. Figure 2 shows the both logging units (Hanford and INEEL) operating at probe holes at the RWMC.

Figure 2 Logging Units in Operation at RWMC

Each of the logging probes equipped with a High Purity Germanium (HPGe) detector (neutron-capture/spectral-gamma and high resolution spectral gamma) contain a down-hole high-voltage power supply transformer, a preamplifier, and a liquid nitrogen dewar. These detectors must be kept at liquid nitrogen temperatures to cool the sensitive solid state detector diode. A filling of the tool dewar will last from 8 to 10 hours. Both the Hanford and INEEL logging trucks contain a bulk liquid nitrogen dewar that provide automatic filling of an HPGe detector when it is not in use in a borehole.

The passive-neutron and neutron-moisture logging tools consist of helium-3 detectors of various dimensions. The neutron-moisture tool is equipped with a neutron source to facilitate acquisition of the moisture measurements. These tools are operated with the same cable and instrumentation utilized for the above mentioned HPGe tools.

The logging cable connects the down hole probes to the logging truck electronics equipment. The cable (Kevlar-reinforced multi-conductor) transmits power to the attached probe and transfers the high precision detector signals to the surface instrumentation. A vent tube within the cable transfers the liquid nitrogen gas vapors from the dewar equipped HPGe detectors up-hole to the logging truck for monitoring of the nitrogen flow rate from the logging tool. The vent tube is inactive when operating the passive-neutron or neutron-moisture probes. Figure 3 shows a logging tool rigged for logging at the RWMC.

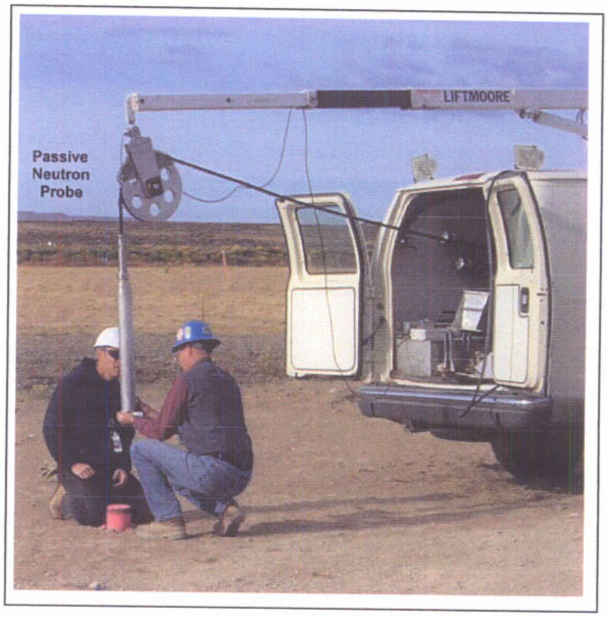

Figure 3 Passive Neutron Logging Tool Operating at RWMC

The cable winch is computer controlled during logging operations. Logging operations are controlled by the computer program Computer Automated Spectral Acquisition System II (CASASII) developed by Greenspan, Inc. The program manages the cable winch and Advanced Data Collection and Management (ADCAM) Multi Channel Analyzers (MCAs) developed by EG&G Ortec, and stores the detector responses as computer files in EG&G Ortec spectral format. Both the neutron and spectral-gamma data are recorded in this format. The CASASII program operates on a PC-AT compatible computer. The computer controlled hoist, winch speed, cable tension sensors, and "watch dog" controls (designed to shut down system in the event of a system malfunction) are integrated as a system for logging at remote locations. The computer controls the position of the logging tool, MCA data collection sequences, and file storage operations.

The schematic of the logging system hardware is shown in Figure 4. A second computer is available on the Hanford logging truck for field review of the raw survey data of previously logged borehole(s), and for analysis and plotting.

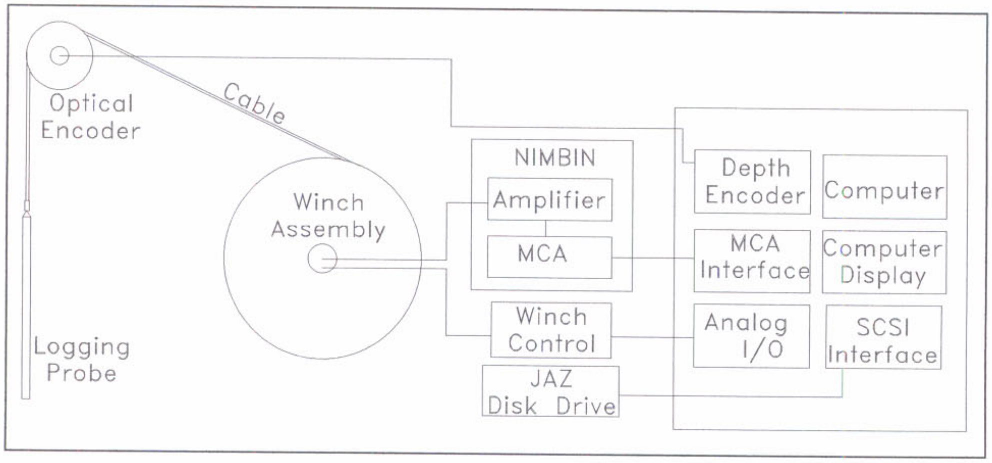

Figure 4 Logging System Hardware Configuration

The depth position of the logging tool is measured with a digital encoder that is mounted on a sheave wheel suspended from the end of a hydraulically articulated support boom. The sheave wheel and boom are positioned over the borehole being logged. The close spacing between boreholes and wide angle of movement of the boom on the Hanford logging truck allowed multiple boreholes to be surveyed from one truck position, minimizing setup time between the boreholes. The INEEL logging truck was generally repositioned for logging each borehole. The Hanford logging truck has a pair of boom support poles (see Figure 2) to stabilize the boom for maximum accuracy of logging tool position. The INEEL logging van is not equipped with boom support poles. The zero depth return error is checked at the end of each borehole survey for both logging trucks and no significant (boom) errors have been identified for either logging truck.

If conditions prevent positioning the logging truck near the borehole, one of the logging trucks can be configured to log at distances up to 40 feet from a borehole by relocating the sheave wheel over the borehole, via crane or tripod.

The surface instrumentation of each logging truck includes a high-precision high-count-rate EG&G Ortec nuclear-spectroscopy amplifier interfaced to the computer-controlled MCA. The number of channels used for data acquisition depends on the resolution required for the measurements. Five hundred (500) channels are adequate for neutron data (passive-neutron and neutron-moisture); 4000 channels are required for HPGe passive spectral-gamma measurements with gamma-ray energies to 2,700 keV; and 8000 channels are utilized for the neutron-capture/spectral-gamma (nGamma) measurement with gamma-ray energies up to 11,000 keV.

A borehole survey is a collection of files consisting of MCA spectra, one spectrum for each measurement station (depth position) in the borehole. A spectrum is generated by precisely measuring the amplitude of each detector signal pulse and incrementing (adding one count) to the MCA channel that corresponds to the voltage level of the signal pulse. A spectrum reflects the gamma ray or neutron flux distribution present at a particular detector position in the borehole and it is depicted as a graph with the MCA channels represented on the x-axis and the number of counts in each channel along the y-axis. Sample spectra for the nGamma, spectral gamma, and passive neutron probes are shown later. The count rate at a measurement station is the sum of the counts in all channels of the spectrum divided by the counting time (Live Time). The live time is the elapsed time the system was available to process detector pulses.

The borehole probes are contained in cylindrical housings of various dimensions and internal configurations. The neutron-moisture logging tool is connected to the logging cable via a cross-over sub-assembly that connects the logging cable connector to the moisture gauge connector. The cross-over also provides the weight needed for logging with the light weight detector and source components.

3.2 Neutron-Moisture Tool

The neutron-moisture tool is an agricultural moisture gauge that has been adapted to borehole conditions encountered in arid climates (i.e. thick unsaturated vadose zone boreholes with steel casing). The moisture gauge is manufactured by Campbell Pacific Nuclear (CPN) in California and the general intended use of the equipment is for boreholes lined with thin wall aluminum tube with diameters only slightly larger than the detector. The adaptation to larger diameter steel cased boreholes was accomplished though construction of appropriate calibration models, extensive analytical studies for hole size and casing size and thickness variations, and computer modeling of formation density variations (Randall, et.al. 1996).

The detector consists of a 50 mCi americium-beryllium (AmBe) neutron source and a helium-3 detector configured to detect thermal-energy neutrons. The detector is 1 in. in diameter and 5.2 in. long. The source-to-detector spacing is 1.2 inches and is considered a zero- or close-spaced instrument. The operating characteristic of a close-spaced neutron-moisture detector is that the detector count rate increases with increasing moisture content. Under the conditions for which this logging tool is calibrated, measurements are reported in percent volumetric moisture content (i.e. vf %, volume fraction percent). As will be discussed later, special calibration was necessary to correlate the neutron-moisture logging tool response to RWMC probe hole conditions, which differed in casing size and thickness, and formation density from the calibration models.

3.2.1 Principle of the Measurements

While logging, the neutron source bombards the formation with energetic neutrons at the rate of thousands per second. A neutron cloud surrounds the source, the radius of which varies with the type of formation materials (or waste) surrounding the borehole and the amount of moisture (hydrogen) in these materials. As the high-energy neutrons are emitted from the source into the formation, they lose energy through collisions with the nuclei of the formation materials; the most significant energy loss occurs from collisions with hydrogen nuclei. The neutrons are eventually slowed to thermal energies (approximately 0.025 eV) and which are efficiently detected by the helium-3 detector in the logging tool. Hydrogen is very efficient at slowing down neutrons, so the logging tool response is primarily a function of the hydrogen concentration of the formation. Borehole and formation environment correction factors are required to accurately compute the moisture content in the subsurface.

The americium-beryllium (AmBe) neutron source is an isotopic alpha-particle source. The alpha particles (nucleus of a helium atom) from the decay of americium react with the beryllium to produce neutrons, as described by the reaction:

$$ {}^{4}_{2}He + {}^{9}_{4}Be \rightarrow {}^{12}_{6}C + {}^{1}_{0}n + Q \text{ (release of energy)} $$

Since this is a chemical source, the alpha-neutron reaction is continually producing neutrons at a constant rate. The radioactivity of the neutron source is low at 50 mCi (0.05 Ci) and has minimal radiological handling restrictions. The CPN moisture gauge is very cost effective, long operating life, dependable, highly repeatable, and has low radiological concerns.

The detector is a ^{3}He filled tube that is manufactured to a pressure of 6 atmospheres. The detector has a voltage pulse output, with one pulse produced by the passage of one neutron through the system via the following reaction.

$$ {}_{2}^{3}He + {}_{0}^{1}n \rightarrow {}_{1}^{3}H + P + 765 keV $$

The detector response is effected by elements in the waste with high thermal neutron capture cross-sections (i.e. neutron absorbers), such as chlorine or cadmium. The presence of neutron absorbers will decrease the detector count rate response; and will be observed as low apparent moisture content. The presence of neutron absorbers and other variables may be able to be identified and evaluated by integrating an epi-thermal neutron-moisture measurement with the system.

3.3 Passive-Neutron Detector

The passive-neutron logging tool has a large (2 in. diameter by 12 in. long), thermal neutron ^{3}He detector that is pressurized to four atmospheres. This tool is described as passive in that no radioactive source is used. At the time that the initial Pit 9 logging was conducted (February 2000), the ^{3}He detector was housed beneath the passive spectral gamma (HPGe) detector. The spacing between the centers of the neutron and HPGe detectors was 0.73 ft. (In this configuration, spectral-gamma measurements could not be acquired within 2.5 ft of the bottoms of the borehole and, since the deeper HPGe measurements were required, this tool has been reconfigured into two (2) tools, each with the minimum distance below the detector.)

The passive-neutron detector was deployed to measure neutrons produced by spontaneous fission or alpha-particle emission of transuranic elements such as ^{241}Am and ^{239}Pu. The detector can not identify the transuranic elements and is therefore not calibrated. The detector response is reported in count rate, i.e. counts per second (c/s) and is used to correct the neutron-moisture log for background neutron activity in the waste. The survey data are integrated with the results of the other logging tools. Correlating the passive-neutron survey results with the passive spectral-gamma logging tool can identify the radionuclides producing neutrons by spontaneous fission.

The detector responds to thermal neutron flux in the subsurface. The detector response, like the neutron-moisture tool, is effected by neutron absorbers in the waste (e.g. chlorine). The presence of neutron absorbers will decrease the observed neutron flux rate (i.e. decrease in the detector count rate response).

3.4 Spectral-Gamma Ray

Three tools selected for the RWMC logging suite contain high-resolution HPGe (high purity germanium) detectors. HPGe detectors provide high-energy resolution that allows unequivocal identification of the radio-isotopic source of the gamma ray emissions. The efficiency rating of the HPGe detectors selected are 10, 20, and 35 percent. The efficiency rating is relative to a sodium iodide (NaI) standard (3-in by 3-in cylindrical) detector.

The 35 percent HPGe detector (high resolution spectral gamma) is used for passive gamma measurements (up to 2,700 keV). The 20 percent HPGe detector is used in the neutron-capture/spectral-gamma tool to detect gamma rays (up to 11,000 keV) resulting from neutron capture by atoms in the formation/waste. A 10 percent HPGe detector (not used for the surveys included in this report) is installed in a heavily shielded housing for the azimuthal (directional) gamma surveys.

3.4.1 Spectral-Gamma Principle of Measurement

Since nuclear decay of radio-isotopes frequently produces gamma rays and the gamma rays have discrete energies, a gamma ray spectrum will contain elevated counts in MCA channels (i.e. photo peaks) that correspond to these gamma ray energies. The radionuclides are identified by the energies of the gamma ray peaks, and the intensity of a gamma ray peak is proportional to the concentration (pCi/g) of the radionuclide.

The concentration for each radionuclide identified in the borehole spectra is determined by applying the detector efficiency calibration coefficients (determined annually by measurements in the borehole calibration models) and applicable corrections factors (thickness of borehole casing and water inside the borehole) to the MCA photo peak intensities. The spectral-gamma borehole calibrations models (located at Hanford and Grand Junction) are traceable by NIST standards and contain enriched concentrations of the naturally occurring radionuclides potassium (K), uranium (U), and thorium (Th) [KUT] that are uniformly distributed in a homogenous matrix of concrete. The concentrations of the radionuclides detected in a borehole are plotted as a function of depth in the borehole, where zero depth corresponds to ground level. A gamma ray spectrum is recorded for each depth position logged. At the RWMC spectra were acquired at depth increment of 0.5-ft.

The intensity in a peak (net count rate) is computed by dividing the net counts of the peak by the Live Time (dead-time corrected counting time). Dead-time occurs when a gamma ray (photon) impinges on a detector and the system is dead or ceases to function for a very short period of time during which the counting system analyzes, measures, and records the detector signal pulse. The net peak counts are the difference between the total peak counts and the background counts (peak counts – background counts = net counts). The background counts compose a background continuum that results from down-scattered gamma rays.

The net peak count rates are corrected for the counting system dead-time (included in net count rate equation) along with the borehole conditions that are different from the calibration models. These conditions attenuate gamma rays emitted from the source (i.e., casing density and thickness and water in the borehole).

The net peak count rates are a linear function of the radionuclide concentration up to a dead-time limit. At higher dead-times the spectra become distorted, peak resolution deteriorates, and the net peak count rate is not a linear relationship of the concentration. The dead-time limit is 32% for the standard length logging cable (600 ft, used in the initial Pit 9 logging) and signal processing electronics configuration for optimum performance. The dynamic range of the logging system has been improved (extended) for logging trucks by reducing the logging cable length to 100 ft and improving the electronics signal processing speed. The dead-time limit is now 85% for the short logging cable (100 ft) and the EG&G Ortec signal processing electronics configured for optimum performance used in this RWMC logging project (APPENDIX A). Both logging trucks are equipped with the short logging cable and properly configured electronics.

Borehole conditions such as the casing density and thickness, and the presence of water inside the borehole, decrease the signal (gamma ray photo peak area) and increase the background continuum of the spectra. The net photo peak count rates are adjusted for these effects with an algorithm to calculate radionuclide concentrations, discussed in Section 4.3.2.

3.5 Neutron-Capture / Spectral-Gamma Logging Tool

The neutron-capture/spectral-gamma (n-Gamma) logging technology allows non-radioactive elements in materials surrounding the borehole to be measured. The tool consists of a 4.0 microgram (as of January 2001) californium-252 (^{252}Cf) neutron source and a 20 percent HPGe detector. The half-life of ^{252}Cf is 2.6 years. The tool diameter is 3.5-in. and length is 5.87-ft. The source-to-detector spacing is 16-in. The measurement location on the n-Gamma logging tool is 1.33-ft above the tool bottom; therefore, measurements closer than this distance above the bottom of the boreholes can not be acquired.

The region of the tool between the source and detector is shielded with tungsten metal to protect the HPGe detector by scattering neutrons into the formation, and to minimize detection of gamma rays from the source. The source is stored in a shielded container when not in use. Installation of the ^{252}Cf source into the lower-end of the logging tool is accomplished with a source handling tool that is designed for this particular application. At the end of logging, the source is removed from the logging tool and returned to its shielded container.

3.5.1 Principle of Measurement

The ^{252}Cf source provides a "cloud" of neutrons which interacts with elements in the formation and waste surrounding the borehole. Atoms that capture the neutrons emit gamma rays that can be measured with the HPGe detector, and the identity of the element can be determined from the energy photo peak(s) of the emitted gamma rays.

Fast neutrons from the source are moderated to thermal energy by the hydrogen in the formation or waste materials surrounding the boreholes. Certain stable elements that occur with sufficient concentration in these materials, and which have sufficient thermal neutron cross-sections, produce a capture gamma ray flux that is measurable in the HPGe spectra. Elements that typically produce strong capture gamma signals are hydrogen, silicon, and iron. Other elements typically present in earth materials such as calcium and aluminum produce weaker gamma rays. Certain elements with large neutron capture cross-sections, such as chlorine, mercury, and cadmium can be detected at relatively low concentrations.

4.0 LOGGING TOOL CALIBRATION

The borehole calibration models and calibration techniques are discussed for each calibrated logging tool used for the RWMC surveys.

The passive-neutron logging tool is not calibrated and data are reported in c/s.

The response characteristics of the n-Gamma probe were characterized in a borehole calibration model and validated by MCNP computer modeling code. However, this calibration is not applicable to the observed formation and borehole conditions. Further development is recommended. The results of the n-Gamma characterization studies are discussed below.

4.1 Neutron-Moisture

4.1.1 Calibration Models

The neutron-moisture logging tool counts thermal-energy neutrons that return to the tool after interactions with the formation materials (especially hydrogen). The calibration relates the probe count rates to the formation moisture content. Calibration models at Hanford provide the means to relate the tool response to moisture content when borehole conditions correspond to conditions in the calibration model. Corrections for differences between the borehole and calibration model are applied with the moisture calculation algorithm (discussed later).

Moisture models were constructed at the Hanford Site for low moisture (partially saturated) soils through a Cooperative Research and Development Agreement (CRADA) between the US-DOE, Pacific Northwest National Laboratory (PNNL), Westinghouse Hanford Company (contractor to US-DOE), and two commercial vendors of geophysical logging services, Halliburton Energy Services and Schlumberger Well Services. Details regarding the construction of the Hanford models are provided in Engelman et. al 1995. Figure 5 shows the moisture models at the Hanford calibration facility. The yellow capped casings on the concrete pads to the right of the moisture models are the underground spectral-gamma ray calibration models (which are discussed later in this report).

Figure 5 Moisture Calibration Models

Laboratory analysis of several thousand drilling samples were used as specifications for the construction of the moisture calibration models. The specifications cover the Hanford formation moisture range and have bulk densities representative of actual formation conditions.

The calibration models consist of seven stainless steel tanks, each with a carbon steel casing through the center, along it axis, for logging tool access. The tank size is sufficiently large, even at low moisture content (increased neutron cloud diameter), that the neutron-moisture measurements experience no edge effects (i.e. appear to be infinite to the detector). Also, the large tank sizes provide for safe operation of large neutron sources, a safety concern since the calibration models are situated above ground.

The contents of the models are comprised of a dry mixture of two components: (1) hydrated alumina {$Al(OH)_3$ or equivalently Al_2O_3 $3H_2O$} and (2) either SiO_2 or Al_2O_3, depending on the required bulk density. The mixture of these components was blended in small batches and as each batch was added to the model, it was vibrated to achieve the maximum bulk density. Hydrated alumina provides the hydrogen and effectively simulates partially saturated formations without the problems associated with using water. The alumina is stable because the water molecules in Al_2O_3 $3H_2O$ are firmly bound and require temperatures greater than 300° C to break the bond.

Al_2O_3 is only used in the model with the thin zone of 40 percent moisture to increase the bulk density of the material in the thin zone without vibrating it for compaction. Vibrating the 40 percent model with the thin zone would have destroyed the interface between the upper and lower low moisture zones. The moisture model specifications are provided in Table 2.

Table 2 Moisture Calibration Models

Model Code	Volume Fraction Water* (vf %)	Bulk Density (g/cm^3)*	Casing ID (in)	Casing Thickness (in)
F	5.0	1.76	6	0.28
E	11.7	1.74	6	0.28
G	19.8	1.70	6	0.28
A	5.0	1.76	8	0.32
C	11.9	1.76	8	0.32
B	19.7	1.70	8	0.32
D (thin zone)	5.0 (top 2.25 ft) 40.9 (mid 1.5 ft) 5.0 (base 2.25 ft)	1.63 1.32 1.55	8	0.32

*Based on the weights of materials and measured dimensions of the model

4.1.2 Neutron-Moisture Calibration

The neutron-moisture logging tool is calibrated in the Hanford moisture models on an annual basis to acquire measurements that will be used to derive the efficiency function of the tool. The logging tool is also calibrated if repairs have been made to the detector that may have been crucial to tool performance. The efficiency function converts the neutron response in c/s to percent volumetric moisture content (vf %). Corrections for borehole size, casing thickness, and bulk density are applied while calculating the moisture content.

During the initial calibration of the moisture gauge, the influences of several borehole configurations were investigated that were anticipated to be encountered in both existing and newly drilled wells/boreholes. The effects of formation density changes, borehole size, casing thickness, multiple casing strings, and grout (cement) between multiple casing strings were investigated and reported by Randall et al. 1996. Monte Carlo modeling calculations, documented in Randall et al., were performed to define the influence of formation characteristics beyond the range of the analytical results.

The instrument response to changes in moisture content is defined by a power law function and has the form:

$$V = aC^{\alpha}$$

where:

V is the calibrated volume fraction of water in vf % units

a and α are the fit coefficients for a specific hole size (OD);
a = 0.0002023, $\alpha = 2.096$, for RLSM10.0 neutron-moisture probe calibration for 5.5 in. O.D. boreholes at RWMC (calibration date Aug. 28, 2000) and

C is the instrument response count rate (c/s) corrected for dead-time and casing thickness; bulk density correction is applied after the conversion to moisture.

The casing attenuation correction factor is defined by the following equation:

$$C = \frac{cr}{1.311 - 0.956t}$$

where:

cr is the dead-time corrected count rate (c/s)

t is the casing thickness (inch)

The bulk density correction is applied after the volume fraction of water is computed by the following equation:

$$VFm = V * \frac{(2.267 * 0.9628) - (0.657 * pb)}{1 + (0.657 * V * 0.01)}$$

where:

V is the volumetric moisture content in vf % units

VFm is the density corrected volume fraction of moisture in vf % units

pb is the bulk density (INEEL specified: 1.43 g/cc)

The RWMC borehole size (5.50 in. O.D.) is different from calibration models and required a linear extrapolation from the (6.56 and 8.68 in. O.D.) calibration standards. The conversion function from detector count rates to moisture content for the RWMC borehole size and calibration model borehole sizes (outside diameter) are shown in Figure 6.

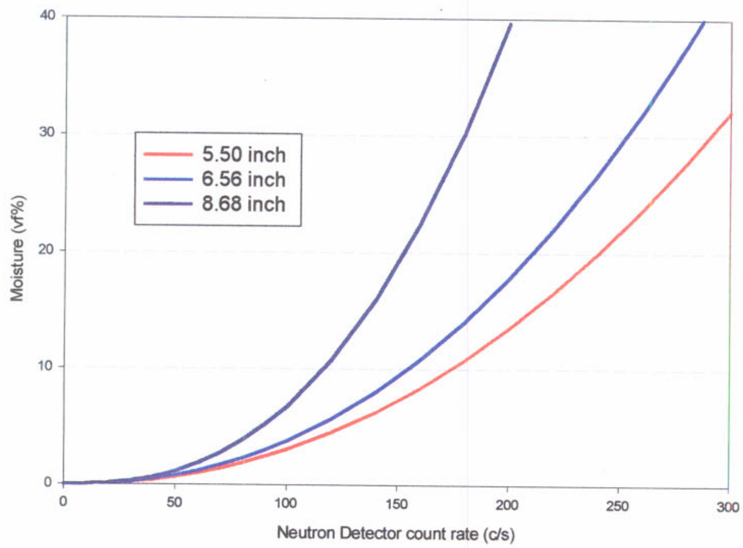

Figure 6 Neutron-Moisture Calibration Function for Three Hole Sizes

Neutron absorbers in the waste will reduce number of neutrons counted by the detector and will cause the apparent moisture to be low.

If a background neutron source is present in the waste the added neutrons generated from the source will increase number of neutrons counted by detector and cause the apparent moisture to be too high. To determine the background neutron contribution to the moisture survey the neutron source in the tool was removed and the moisture detector was run in several boreholes (P920, 743-4, 743-5, 743-12) to determine the background neutron contribution. The background moisture detector surveys (without the neutron source) were compared with the passive neutron surveys to establish a conversion factor between the two detectors (1:6 ; 1 c/s moisture detector = 6 c/s passive neutron detector). A correction to the neutron-moisture survey data for background neutrons in the waste has been applied based on the passive neutron log survey data.

Performance of the neutron-moisture logging tool is verified in the field before and after acquiring log data, and by acquiring a repeat log interval. The count rate of the detector is observed while the shield is attached to the probe and is recorded on the Borehole Survey Data Sheet for the particular survey. This count rate is compared with that observed during the annual tool calibration and with the previous surveys.